

Peeling-off of the external kink modes at tokamak plasma edge

L. J. Zheng^{a)} and M. Furukawa^{b)}

^{a)}*Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712*

^{b)}*Graduate School of Engineering, Tottori University, Tottori 680-8552, Japan*

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Abstract

It is pointed that there is a current jump between the edge plasma inside the last closed magnetic surface and the scrape-off layer and the current jump can lead the external kink modes to convert to the tearing modes, due to the current interchange effects [L. J. Zheng and M. Furukawa, Phys. Plasmas 17, 052508 (2010)]. The magnetic reconnection in the presence of tearing modes subsequently causes the tokamak edge plasma to be peeled off to link to the diverters. In particular, the peeling or peeling-ballooning modes can become the “peeling-off” modes in this sense. This phenomenon indicates that the tokamak edge confinement can be worse than the expectation based on the conventional kink mode picture.

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I. INTRODUCTION

The H-mode confinement — an operating mode with high energy confinement¹ — has today been adopted as a reference for next generation tokamaks, especially for ITER. However, the H-mode confinement is often tied to the damaging edge localized modes (ELMs).¹ There is a concern that ELMs can discharge particles and heat into the scrape-off layer and subsequently to the diverters. The diverter plates can be potentially damaged by such a discharge. This is particularly a concern for big devices like ITER.

This concern has stimulated active researches in this field for clarifying the tokamak plasma edge instabilities, in order to understand the ELMs. The most well-known theories are the peeling and the peeling-ballooning modes.^{2,3} However, the peeling or peeling ballooning modes are of kink type. Without field line reconnection the plasmas inside the last closed surface actually are not peeled off.

The necessity to consider the tearing mode excitation and the coupling of the scrape-off-layer current was first pointed out in Ref. 4. Apparently, to understand the ELMs one needs to take into consideration the subtle feature of tokamak plasma edge, where the plasma on one side is confined in the closed surfaces and on the other side the plasma is linked to the diverters due to the open-field-line feature in the scrape-off layer. Otherwise, one cannot explain why there is not any ELM-type of bursting at the internal transport barrier. The development of tearing modes can effectively connect the pedestal plasma to the scrape-off layer. Taking into account this edge feature Ref. 4 proposed a current-driving-mode theory for ELMs. The magnetohydrodynamic (MHD) mode at plasma edge can be amplified due to the nonlinear coupling with scrape-off-layer current. This coupling can be a positive feed-back process and lead to the ELM bursting. The theory explains many characteristic features of ELMs as observed at tokamak experiments, such as a sharp onset and initial fast growth of magnetic perturbations even when the underlying equilibrium is only marginally unstable for a MHD mode and also a quick quenching after the bursting peak. This work also points to the current driven modes — tearing type — as the ELM bursting explanation, although the kink type of modes, such as the peeling ballooning modes, can be a trigger.

In this paper we further explain how the external kink modes in tokamaks, such as the peeling ballooning modes, can become a trigger to the excitation of tearing modes. We point out that there is a current jump between the plasma edge inside the last closed surface

and the scrape-off layer. When there is a plasma perturbation at the edge, the currents on each side of the jump are carried over alternatively in the opposite direction to form a perturbed current sheet (see Fig. 1). This current sheet can lead to the excitation of tearing modes. This mechanism reflects the extreme case of the current interchange tearing modes as pointed out in Ref. 6, with the tokamak edge and scrape-off layer specialties being taken into consideration. Note that the drive to the current interchange tearing modes, as pointed out in Ref. 6, is proportional to the current gradient. The current jump between the plasma edge and the scrape-off layer make the drive at the edge to be dramatically enhanced. As shown in the later on analysis, the conversion of external kink modes to tearing modes at tokamak edge can therefore happen readily and cause the edge plasma to be peeled off. Note that this process may be positively fed back, as pointed out in Ref. 4. This phenomenon indicates that the tokamak edge confinement can be worse than the expectation based on the conventional kink mode picture.

We prove this peeling-off phenomenon by re-deriving the nonlinear tearing mode equation, which was originally developed by P. H. Rutherford.⁷ Note that Ref. 7 intended to consider the resistivity/current gradient effects. However, it only took into consideration the thermal conductivity effects related to the current gradient, without including the current convective effect as pointed out in Ref. 6. The current convective effect at the plasma edge can be very significant due to the jump between the plasma edge and the scrape-off layer. This motivates us to examine this issue.

This paper is arranged as follows: Following to this introduction section, in Sec. II the Rutherford's equation will be rederived with the current jump between the plasma edge and scrape-off layer being taken into account; The results will be summarized and discussed in the last section, Sec. III.

II. REDERIVATION OF RUTHERFORD'S EQUATION AT THE PLASMA EDGE

In this section we will rederive the Rutherford's equation in Ref. 7 to include the effects of the current jump between the plasma edge and scrape-off layer. We first describe the Ohm's laws for the edge plasma and the scrape-off layer. For the edge plasma inside the last closed surface Ohm's law is

$$j_{\parallel} = \sigma E_{\parallel}, \quad (1)$$

where j is the current density, E represents the electric field, σ is the conductivity, with resistivity being $\eta = 1/\sigma$, and subscript \parallel denotes the parallel direction. In the scrape-off layer the field lines are connected to diverters at the both ends, indicated by A and B . The generalized Ohm's law in the scrape-off layer was derived in Ref. 8:

$$j_{\parallel} = \sigma_v E_{\parallel} - \gamma(0.85 - \alpha)j_{SAT} \frac{T_B - T_A}{T_A}, \quad (2)$$

where

$$\begin{aligned} j_{\parallel} &= j_{SAT} \hat{j}_{\parallel}, \\ \hat{j}_{\parallel} &= -\gamma \left\{ \frac{e\phi_0}{T_A} + (\kappa + 0.85 - \alpha) \left(\frac{T_B}{T_A} - 1 \right) \right. \\ &\quad \left. + \ln \left[\frac{1 + \hat{j}}{(1 - (T_B/T_A)^{1/2} \hat{j}_{\parallel})^{T_B/T_A}} \right] \right\}, \\ j_{SAT} &= \frac{1}{2^{3/2}} en C_s, \\ \sigma_v &= \frac{e^2 \lambda_{11} L_{\parallel}}{m_e} \left[\int_A^B \frac{dl_{\parallel}}{n_e \tau_{ei}} \right]^{-1}, \\ \gamma &= \frac{\hat{\sigma} T_A}{e L_{\parallel} j_{SAT}}, \\ \kappa &= \frac{1}{2} \ln \left(\frac{2m_i}{\pi m_e} \right) = 3.89. \end{aligned}$$

Here, e is the elementary charge, m is the mass, n is the density, T denotes the temperature, ϕ is the electric potential, $\phi_0 = \phi_B - \phi_A$, C_s is the sound speed, $\alpha = \lambda_{12}/\lambda_{11}$, λ_{11} and λ_{12} are the Spitzer-Harm coefficients,⁹ τ_{ei} is the electron-ion collisional time, L_{\parallel} denotes the connection length between both ends A and B , l_{\parallel} is the arc length along magnetic field line, subscripts e and i represent respectively the electron and ion quantities, and subscripts A and B denote quantities at the ends A and B , respectively. Note here that the Ohm's laws in Eqs. (1) and (2) are given the moving frame. In the laboratory frame the electric field \mathbf{E} needs to be replaced by $\mathbf{E} + \mathbf{v} \times \mathbf{B}$. Here, we use the bold face to denote vectors, \mathbf{B} denotes the magnetic field, and \mathbf{v} is the fluid velocity.

As Ref. 7 we use the slab model in the (x, y, z) space, with $x = 0$ specifying the rational surface and z representing the longitudinal direction. The coordinate system is shown in Fig. 1. The flux function ψ and the stream function φ are introduced to represent the magnetic field $B_x = -\partial\psi/\partial y$, $B_y = \partial\psi/\partial x$ and the velocity $v_x = -\partial\varphi/\partial y$, $v_y = \partial\varphi/\partial x$. Here, the subscripts (x, y, z) are introduced to denote the corresponding projections. We also introduce the displacement $\boldsymbol{\xi}$, which is related to the velocity by $\partial\boldsymbol{\xi}/\partial t = \mathbf{v}$.

We consider the equilibrium with magnetic shear, in which the poloidal magnetic field is represented by $B_y = B'_y x$. Here, prime is used to denote the derivative with respect to x . The total magnetic flux can be written as⁷

$$\psi(x, y, t) = \psi_0(x) + \delta\psi(y, t), \quad (3)$$

where $\psi_0(x) = B'_y x^2/2$ is the equilibrium value, $\delta\psi(y, t) = \delta\psi_1(t) \cos ky$ is the perturbed value, and k is the poloidal wave number. We use subscript 0 to denote the unperturbed quantities and “ δ ” to tag the perturbed quantities. Nevertheless, the subscript 0 is dropped as soon as there is no ambiguity with the total quantities. The purpose of this work is to prove that, if there is a free-boundary kink mode, it can be converted to the tearing modes due the current jump from the plasma region inside the last closed surface to the scrape-off layer. Therefore, we assume that there is a kink perturbation at the plasma edge as follows

$$\xi = \xi_0 + \xi_1 \cos ky. \quad (4)$$

Here, ξ_0 is used to specify the distance between the last closed surface and the rational surface. Note that at the plasma edge the magnetic shear is very large, the distance between the last closed surface and the rational surface can be very small, so that one may assume $\xi_0 \rightarrow 0$. We also note that the kink modes have different parity from that of tearing modes. Although there is finite $\xi - \xi_0$ at the rational surface, the direct effect of $(\xi - \xi_0)$ on $\delta\psi$ is negligible, since $\delta\psi \sim x(\xi - \xi_0)$. The effects of the displacement $(\xi - \xi_0)$ to be considered in this work is the formation of current sheet due to the convective carrying-over of equilibrium current. In difference from Ref. 7, in which the $\xi - \xi_0$ turbulence effects on the tearing modes through the thermal conduction are considered, in this work we consider the convective effect on the formation of the current sheet.

As usual, we use the Ampere’s law and the field diffusion equation to construct the basic set of equations. The Ampere’s law gives

$$\frac{d^2 \delta\psi}{dx^2} = \mu_0 \delta j_z, \quad (5)$$

where μ_0 is the magnetic constant.

As for the field diffusion equation, we have to consider separately the edge plasma region ($x \leq 0$) inside the last closed surface and the scrape-off layer ($x > 0$). We first consider the edge plasma region ($x \leq 0$). The derivation of the field diffusion equation is similar to that

in Ref. 7. Using Faraday's law one obtains $\delta E_z = \partial \delta \psi / \partial t$. Using this expression and the velocity representation with $\delta \varphi$, the curl operation of Ohm's law in Eq. (1) yields

$$\frac{\partial \delta \psi}{\partial t} - \frac{\partial \delta \varphi}{\partial y} B'_y x = \delta(\eta j_z). \quad (6)$$

Here, as discussed previously, the $\mathbf{v} \times \mathbf{B}$ effect has been added in the Ohm's law Eq. (1). The perturbed quantity $\delta(\eta j_z)$ in Eq. (6) contains both the local inductive ($\partial/\partial t$) and convective ($\mathbf{v} \cdot \nabla$) contributions due to the presence of the displacement ξ in Eq. (4) (see Fig. 1). We exclude the inhomogeneity effects of the plasma resistivity both in the edge plasma region (η) and in the scrape-off layer (η_v) from our consideration, since they are smaller than the effects from the current jump between the edge plasma and the scrape-off layer. In consistence with this we also ignore the inhomogeneity effects of other thermal quantities, such as n and T . In the region where the edge plasma is not taken over by the scrape-off-layer plasma we then have

$$\delta(\eta j_z) = \eta \delta j_z. \quad (7)$$

Instead, in the region where the edge plasma is replaced by the scrape-off-layer plasma one has to include the convective effects due to the displacement ξ . This yields

$$\begin{aligned} \delta(\eta j_z) &= \eta_v j_z + \gamma(0.85 - \alpha) \eta_v j_{SAT} \frac{T_B - T_A}{T_A} - \eta j_{z0} \\ &= \eta_v \delta j_z - \Delta \hat{E}, \end{aligned} \quad (8)$$

where the electric field jump reads

$$\Delta \hat{E} \equiv \eta j_{zp0} - \left[\eta_v j_{zv0} + \gamma(0.85 - \alpha) \eta_v j_{SAT} \frac{T_B - T_A}{T_A} \right].$$

Here, j_{zp0} and j_{zv0} denote the equilibrium current densities respectively in the plasma edge and the scrape-off layer. Using Eqs. (7) and (8), the diffusion equation in the edge plasma region ($x < 0$), Eq. (6), can be expressed as

$$\frac{\partial \delta \psi}{\partial t} - \frac{\partial \delta \varphi}{\partial y} B'_y x = H(\xi - x) \eta \delta j_z + H(x - \xi) \left(\eta_v \delta j_z - \Delta \hat{E} \right), \quad (9)$$

where, $H(x)$ is the Heaviside step function. Similarly, the diffusion equation in the scrape-off layer ($x > 0$) can be obtained as

$$\frac{\partial \delta \psi}{\partial t} - \frac{\partial \delta \varphi}{\partial y} B'_y x = H(x - \xi) \eta_v \delta j_z + H(\xi - x) \left(\eta \delta j_z + \Delta \hat{E} \right). \quad (10)$$

The current jump between the edge plasma and scrape-off layer and the inclusion of the convective effects make the diffusion equations (9) and (10) become different from that in Ref. 7.

To proceed to derive the tearing mode equation, we still need to consider separately the edge plasma region ($x \leq 0$) and the scrape-off layer ($x > 0$). We first treat the edge plasma region ($x \leq 0$). Dividing by x and averaging over y at constant ψ to eliminate the second term on the left, equation (9) becomes

$$\frac{1}{\mu_0} \frac{\partial^2 \delta\psi}{\partial x^2} = \frac{\left\langle \frac{\partial \delta\psi / \partial t}{(\psi - \delta\psi)^{1/2}} \right\rangle + \left\langle \frac{H(x-\xi) \Delta \hat{E}}{(\psi - \delta\psi)^{1/2}} \right\rangle}{\left\langle \frac{H(\xi-x)\eta + H(x-\xi)\eta_v}{(\psi - \delta\psi)^{1/2}} \right\rangle}, \quad (11)$$

where $\langle \dots \rangle = (k/2\pi) \int_0^{2\pi/k} \{ \dots \} dy$. Here, we have used Eq. (5) to express δj_z on the left hand side and noted that $\delta j_z(\psi)$ is a function of ψ only as required by the reduced vorticity equation $\mathbf{B} \cdot \nabla \delta j_z = 0$, proved in Ref. 7. Further integration over x from $-\infty \rightarrow 0$ of Eq. (11) yields

$$\left. \frac{\partial \delta\psi}{\partial x} \right|_{-\infty}^0 = -\frac{\mu_0}{\sqrt{2B'_y}} \int_{-\infty}^0 \frac{d\psi}{(\psi - \delta\psi)^{1/2}} \frac{\left\langle \frac{\partial \delta\psi / \partial t}{(\psi - \delta\psi)^{1/2}} \right\rangle + \left\langle \frac{H(x-\xi) \Delta \hat{E}}{(\psi - \delta\psi)^{1/2}} \right\rangle}{\left\langle \frac{H(\xi-x)\eta + H(x-\xi)\eta_v}{(\psi - \delta\psi)^{1/2}} \right\rangle}.$$

Multiplying $\cos ky$ and averaging over y this equation is reduced to

$$\begin{aligned} \frac{\left. \frac{\partial \delta\psi_1}{\partial x} \right|_{-\infty}^0}{\delta\psi_1} \delta\psi_1 &= -\frac{2\mu_0}{\sqrt{2B'_y}} \frac{\partial \delta\psi_1}{\partial t} \int_{-\infty}^0 d\psi \frac{\left\langle \frac{\cos ky}{(\psi - \delta\psi)^{1/2}} \right\rangle^2}{\left\langle \frac{H(\xi-x)\eta + H(x-\xi)\eta_v}{(\psi - \delta\psi)^{1/2}} \right\rangle} \\ &\quad - \frac{2\mu_0}{\sqrt{2B'_y}} \int_{-\infty}^0 d\psi \frac{\left\langle \frac{\cos ky}{(\psi - \delta\psi)^{1/2}} \right\rangle \left\langle \frac{H(x-\xi) \Delta \hat{E}}{(\psi - \delta\psi)^{1/2}} \right\rangle}{\left\langle \frac{H(\xi-x)\eta + H(x-\xi)\eta_v}{(\psi - \delta\psi)^{1/2}} \right\rangle}. \end{aligned} \quad (12)$$

Introducing the dimensionless quantities $w = \psi/\delta\psi_1$, $\Delta E = \mu_0 \Delta \hat{E}/(\eta B'_y)$, $\Delta'_- = \left. \frac{\partial \delta\psi_1}{\partial x} \right|_{-\infty}^0 / \delta\psi_1$, and the island width $x_T = 2\sqrt{\delta\psi_1/B'_y}$, one obtains from Eq. (12)

$$\begin{aligned} \Delta'_- &= \frac{\mu_0 \sqrt{2}}{\eta} \frac{\partial x_T}{\partial t} \int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle^2}{\left\langle \frac{H(\xi-x) + H(x-\xi)(\eta_v/\eta)}{(w - \cos ky)^{1/2}} \right\rangle} \\ &\quad + \frac{2\sqrt{2}}{x_T} \int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle \left\langle \frac{H(x-\xi) \Delta E}{(w - \cos ky)^{1/2}} \right\rangle}{\left\langle \frac{H(\xi-x) + H(x-\xi)(\eta_v/\eta)}{(w - \cos ky)^{1/2}} \right\rangle}. \end{aligned} \quad (13)$$

Similarly, in the scrape-off layer ($x > 0$) one has

$$\begin{aligned} \Delta'_+ = & \frac{\mu_0 \sqrt{2}}{\eta} \frac{\partial x_T}{\partial t} \int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle^2}{\left\langle \frac{H(\xi - x) + H(x - \xi)(\eta/\eta)}{(w - \cos ky)^{1/2}} \right\rangle} \\ & - \frac{2\sqrt{2}}{x_T} \int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle \left\langle \frac{H(\xi - x) \Delta E}{(w - \cos ky)^{1/2}} \right\rangle}{\left\langle \frac{H(\xi - x) + H(x - \xi)(\eta/\eta)}{(w - \cos ky)^{1/2}} \right\rangle}, \end{aligned} \quad (14)$$

where $\Delta'_+ = \frac{\partial \delta \psi_1}{\partial x} \Big|_0^{+\infty} / \delta \psi_1$. Combining Eqs. (13) and (14) one finally obtains the tearing mode equation:

$$\Delta' = \frac{2\sqrt{2}\mu_0}{\eta} \frac{\partial x_T}{\partial t} A_0 - \frac{2\sqrt{2}}{x_T} A_c, \quad (15)$$

where $\Delta' = \Delta'_- + \Delta'_+$ and

$$\begin{aligned} A_0 = & 0.5 \left[\int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle^2}{\left\langle \frac{H(\xi - x) + H(x - \xi)(\eta/\eta)}{(w - \cos ky)^{1/2}} \right\rangle} \Bigg|_{x < 0} + \int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle^2}{\left\langle \frac{H(\xi - x) + H(x - \xi)(\eta/\eta)}{(w - \cos ky)^{1/2}} \right\rangle} \Bigg|_{x > 0} \right], \\ A_c = & - \int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle \left\langle \frac{H(x - \xi) \Delta E}{(w - \cos ky)^{1/2}} \right\rangle}{\left\langle \frac{H(\xi - x) + H(x - \xi)(\eta/\eta)}{(w - \cos ky)^{1/2}} \right\rangle} \Bigg|_{x < 0} + \int_{-1}^{+\infty} dw \frac{\left\langle \frac{\cos ky}{(w - \cos ky)^{1/2}} \right\rangle \left\langle \frac{H(\xi - x) \Delta E}{(w - \cos ky)^{1/2}} \right\rangle}{\left\langle \frac{H(\xi - x) + H(x - \xi)(\eta/\eta)}{(w - \cos ky)^{1/2}} \right\rangle} \Bigg|_{x > 0}. \end{aligned}$$

Equation (15) is the modified Rutherford equation with the convective effects being taken into account at the plasma edge, where there is a current jump. Note that in Eq. (15) Δ' can be obtained from the outer solution, A_0 specifies the inductive contribution, and A_c the convective contribution. Letting $A_c = 0$ (i.e., $\Delta E = 0$) and $\eta = \eta_v$, equation (15) reduces to the usual Rutherford equation given in Ref. 7. From Fig. 1 one can see that in the region for $H(x - \xi) = 1$ and $x < 0$ one usually has $\cos ky < 0$; and in the region for $H(\xi - 1) = 1$ and $x > 0$ one usually has $\cos ky > 0$. Therefore, one usually has $A_c > 0$. This shows that the convective contribution from the current jump is generally a driving term for tearing modes.

Using the Ampere's law one can get the ordering estimate: $\Delta E \sim \mathcal{O}(1)$. Noting that the second term on the right hand side of Eq. (15) is inversely proportional to the island width x_T , the convective driving contribution can be very large. In the case with the current varying smoothly without a steep jump the convective driving term is proportional to the displacement ξ_1 as shown in Ref. 6. In the current case the current jump significantly enlarges the convective driving effects in Eq. (15). Note that the kink mode has a different

parity from that of the tearing mode. However, the inclusion of the current convective effects causes the two types of modes to become coupled. This makes the kink mode is prone to convert to the current interchange tearing modes at the plasma edge.

To show the magnitudes and parameter dependences, we numerically compute the two parameters A_0 and A_c using the NAG (Numerical Algorithms Group) mathematical libraries, especially the subroutine D01APF. We consider the case with $\xi_0 \rightarrow 0$. Figure 2 shows the dependence of A_0 on the resistivity ratio η_v/η . The displacement ξ_1 is used as a parameter in this figure, which is normalized by x_T . Figure 3 shows the dependence of A_c on the electric field jump ΔE , with the resistivity ratio η_v/η as parameter. Figure 4 shows the dependence of A_c on the normalized displacement ξ_1 with the resistivity ratio η_v/η and the electric field jump ΔE as parameters. The calculations show that the dominant contributions come from the current inside the magnetic island. From the parameter scans in these figures one can see that A_c is of order unity. Equation (15) shows that the convective contribution can be very big as compared to Δ' . This indicates that the perturbations of kink type at the plasma tend to convert to the tearing modes, due to the current jump between the edge plasma and the scrape-off layer.

III. CONCLUSIONS AND DISCUSSION

The release of thermal energy by tokamak plasma kink modes has been widely studied in this field. In this paper we show that the kink modes can carry over the equilibrium current and leads to the formation of the current sheet at the singular layer. Due to the vast difference between the equilibrium currents in the edge plasma and the scrape-off layer, the current sheet can induce the tearing modes. This is an extreme case of the so-called current interchange tearing modes at the plasma edge as pointed out in Ref. 6, with the tokamak edge and scrape-off layer specialties being taken into consideration. Due to the current jump between the edge plasma and the scrape-off layer, the driving effects for current interchange tearing modes at the plasma edge can be very big. Practically, any kink perturbations on the plasma edge are potentially induce the tearing modes. The direct consequence of the excitation of the current interchange tearing mode at the plasma edge is that the confined plasma inside the closed magnetic surfaces can be peeled off to the scrape-off layer and then to the diverters. As an example, the peeling or peeling-ballooning modes can become the

“peeling-off” modes in this sense.

What is more, Ref. 5 points out that the pumping out of the confined plasma in the closed surfaces to the scrape-off layer can enhance the scrape-off-layer current, especially because the plasma edge usually carries the negative charges, while the diverter sheets are excessive in the positive charges. The the scrape-off-layer current can further drive the tearing modes and causes the positive feedback process. Therefore, the current work can help to explain further the edge localized modes in the H-mode confinement.

Note that there is a similarity between the edge localized modes and the tokamak major disruptions. In the edge localized mode case the scrape-off layer current is excited; while in the disruption case the halo current is induced. Both are explosive nonlinear processes and involve plasma and wall interaction. One is in a small scale; and the other is in a large scale. Peeling off the confined plasma in the closed surfaces to the scrape-off layer or wall due to the current interchange tearing modes at the plasma edge may also help to explain the disruption, especially the generation of the halo current and its feedback.

In passing, we note that the current work has not included the neoclassical tearing modes,^{10,11} although in principle the current interchange can include the interchange of the bootstrap current. This will be investigated in the future.

In conclusion, the possible excitation of current interchange tearing modes at the plasma edge due to the current jump indicates that the tokamak edge confinement can be worse than the expectation based on the pressure driven (or kink) instabilities alone.

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Figure captions

Fig. 1: The coordinate system for analyzing the current interchange effects. The axis z points out of the paper. The perturbed current directions are indicated. The edge plasma locates at the $x < 0$ region, while the scrape-off layer at the $x > 0$ region. The plasma displacement ξ is plotted by the dashed curve with $\xi_0 = 0$ assumed.

Fig. 2: The parameter A_0 versus the resistivity ratio η_v/η with the displacement ξ_1 as parameter.

Fig. 3: The parameter A_c versus the electric field jump ΔE , with the resistivity ratio η_v/η as parameter. The normalized displacement $\xi_1 = 1$ is assumed.

Fig. 4: The parameter A_c versus the normalized displacement ξ_1 , with the resistivity ratio η_v/η and the electric field jump ΔE as parameters.

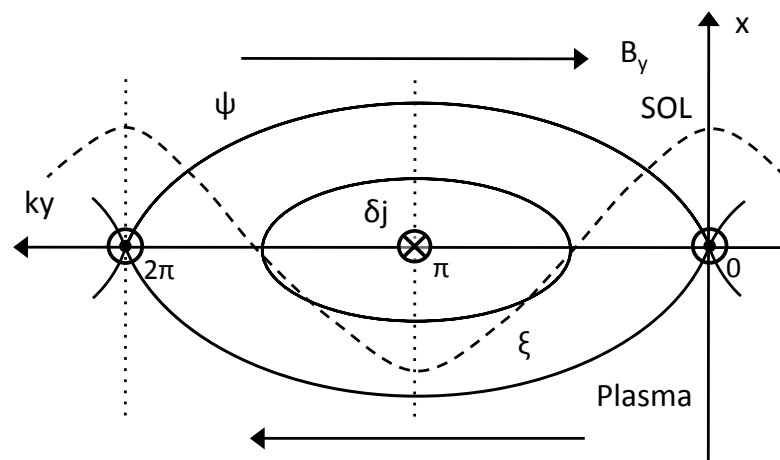


Fig. 1

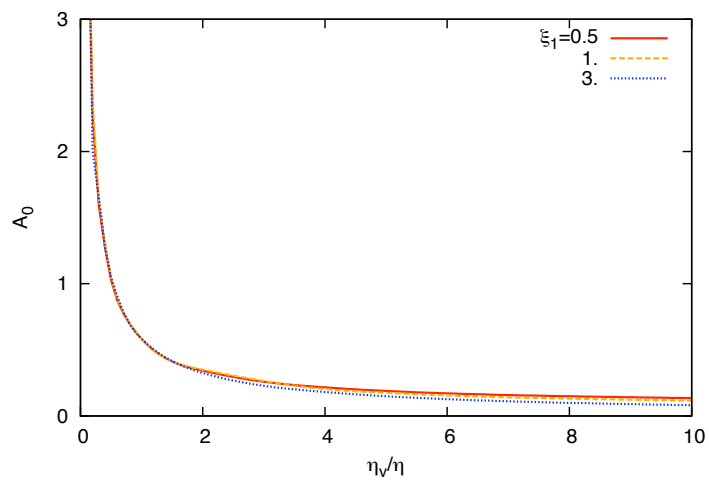


Fig. 2

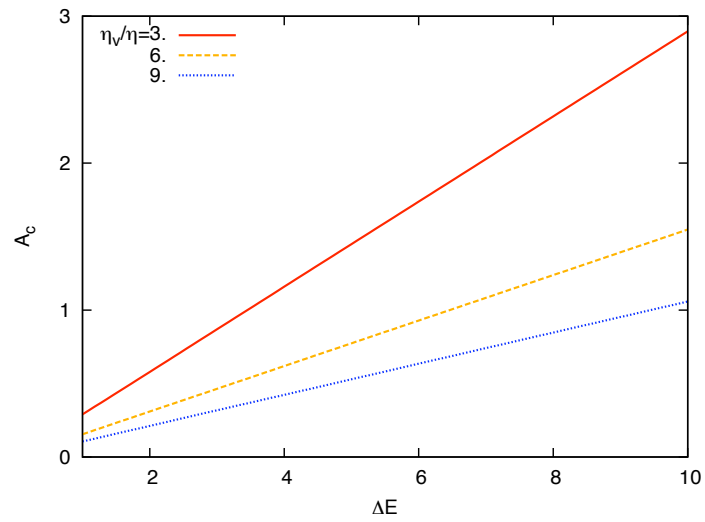


Fig. 3

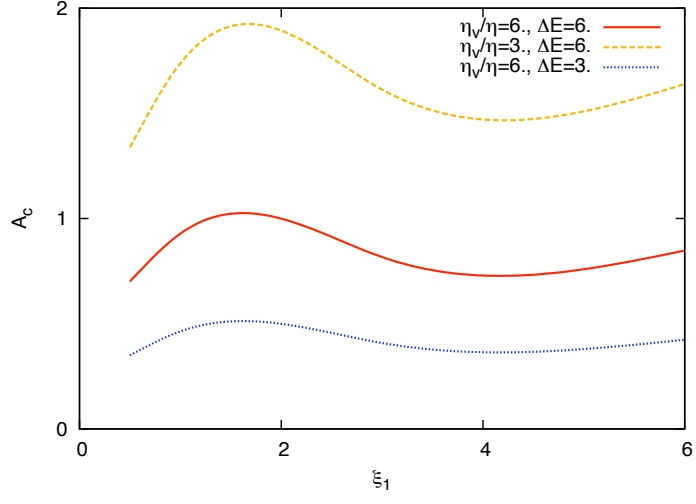


Fig. 4